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Note No. 4 on the Theory of Bomb Stability

by

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SUMMARY

The three previous notes* in this series have outlined the theory of the motion of a bomb recovering from disturbances on the assumption that the bomb was stable. This note outlines the different types of instability - cartwheeling, undamped spinning, and whirling - and describes the aerodynamic basis of the methods of eliminating them.

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1 Cartwheeling

If the centre of pressure is ahead of the centre of gravity, in axial flight the bomb will be in unstable equilibrium and a small disturbance will introduce a de-stabilising aerodynamic moment. There is no position of stable equilibrium and the bomb never assumes a fixed attitude to its flight path but tumbles all over the place, or "cartwheels"; the motion is completely disorderly.

The cure for this form of instability may be attempted by moving the centre of gravity forwards or the centre of pressure backwards; the former method involves a change in the mass distribution but may leave the external shape unaltered, whereas the latter changes the external shape and may make a negligibly small change in the centre of gravity position. In order to shift the centre of pressure backwards the lift on the nose of the bomb may be greatly reduced by using a nose spoiler (Arm. Dept. Note No. Arm.167) or the lift at the rear increased by a redesign of the tail.

2 Undamped Spinning

Bombs are sometimes observed oscillating or spinning with almost constant amplitude; at any rate, the amplitude does not change rapidly. This type of motion is more often noted late in flight rather than very early in flight, and arises from poor airflow over the tail.

Good stability requires that a large restoring moment shall be generated at small angles of incidence, and this requires that the tail drum or a reasonably large area of fin shall be out of the wake from the body. Unless this condition is satisfied, the tail surfaces

* Previous Notes: Tech. Notes Nos. Arm.61, 81 & 167.

do not develop lift effectively. If the tail is in the wake when the bomb is in axial flight, there will be a range of incidence in which the restoring moment is negative, zero, or very small, until a critical angle is reached at which the tail surfaces begin to be free of the wake. A restoring moment of reasonable magnitude is then developed. The bomb can therefore spin with a cone semi-angle roughly equal to this critical angle, and the result is undamped spinning.

The wake diameter is markedly dependent on the degree of "break away" of airflow at the junction of the tail cone and the bomb body, in bombs which are not fully streamlined. Breakaway becomes more severe at higher speeds, hence the tendency of the undamped spin to occur late in flight - at higher speeds - as the wake diameter increases. When the speed becomes so high that shock waves begin to develop from the bomb body, breakaway at first becomes more severe but at still higher speeds - as the point of formation of shock waves moves back along the body - conditions may improve again.

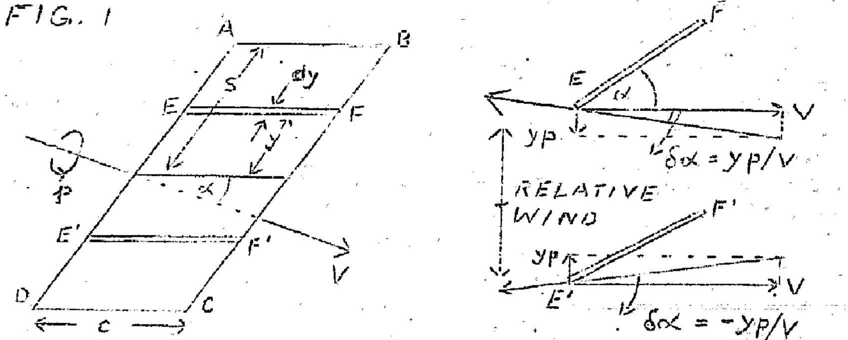
This type of instability can be cured by ensuring that the tail surfaces are not in the wake from the body. The tail or body must be redesigned in order to reduce the wake diameter, or lift surfaces must must be placed outside the wake diameter (e.g. expanding fins). Part of the tail surfaces may be shielded if the body lacks symmetry or the tail is not squarely fitted and the bomb may execute undamped spins even though it would have been very stable if accurately made and assembled.

3 Whirling

A type of instability particularly liable to occur in bombs which receive a violent disturbance on release is "whirling"; the bomb flies with its axis at a large angle of incidence to the direction of motion and rotates rapidly. This may be called a flat spin and is akin to the autorotation of aeroplanes; it is a stable state.

In considering how this type of motion arises the fundamental principles are made clearer by considering an aerofoil rather than a bomb.

FIG. 1



Consider (Figure 1) a rectangular aerofoil ABCD of span 2s and chord c flying at incidence α to a relative wind speed V. Let the aerofoil be given an angular velocity of rotation p about the relative wind and consider an element EF distant y from the centre and of breadth dy.

With the rotation as shown, EF moves downward and its angle of incidence is therefore <u>increased</u> by an angle yp/V; the corresponding element E'F' on the other side suffers a <u>decrease</u> of incidence yp/V. If dL is the element of rolling moment due to EF and E'F' and is measured in the same direction as p, then

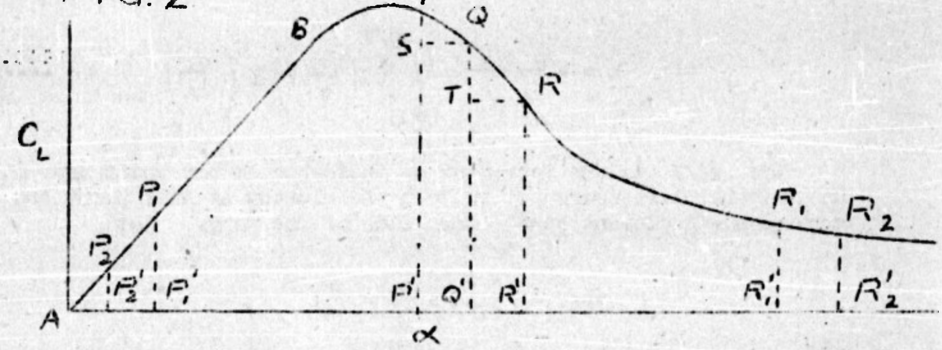
$$dL = -\tfrac{1}{2}\,(\delta C_L).\rho.\ c\ dy.\ V^2.\ y + \tfrac{1}{2}\,(\delta C_L').\rho.\ c\ dy.\ V^2.\ y$$

or $$dL = -\tfrac{1}{2}\,\rho\ c\ y\ V^2\,(\delta C_L - \delta C_L')\ dy \qquad \text{......(1)}$$

where δC_L and $\delta C_L'$ are the positive increments of lift coefficient on EF and E'F' due to rotation; they are, of course, dependent on yp/V.

A typical lift coefficient-incidence curve is shown in Fig. 2. Along AB the lift coefficient increases roughly linearly with incidence, and at C the maximum lift coefficient is reached; this point is known as the stall. Thereafter the lift coefficient begins to decrease as incidence increases.

FIG. 2



Supposing in the case we are considering conditions are such that the maximum incidence $\alpha + sp/V$ and the minimum $\alpha - sp/V$ both lie in the straight portion AB of the $C_L - \alpha$ curve, then in the equation we have obtained for dL, assuming $\frac{dC_L}{d\alpha}$ is constant:

$$\delta C_L = -\delta C_L' = \frac{dC_L}{d\alpha}.\frac{yp}{V}$$

Hence $$dL = -\tfrac{1}{2}\,\rho\ c\ V^2\ y.\ 2\,\frac{yp}{V}.\frac{dC_L}{d\alpha}.\,dy$$

or $$dL = -\rho\ c\ V\ y^2\ p\,\frac{dC_L}{d\alpha}\ dy$$

Integrating this equation for the whole wing gives

$$L = -\frac{1}{3}\,\rho\ c\ s^3\ p\ V\,\frac{dC_L}{d\alpha} \qquad \text{......(2)}$$

This quantity is negative and is usually large, hence any tendency to roll is opposed by a couple which damps it out.

Suppose, now, that the wing had been stalled before rotation, its incidence corresponding to Q' in Figure 2. The incidences of EF and E'F' are then represented by R' and P' where

$$P'Q' = Q'R' = yp/V.$$

It is clear that δC_L = QT and is negative while $\delta C_L'$ = SP and is positive; hence let

$$\delta C_L - \delta C_L' = \Delta \quad (= -TQ - SP)$$

where Δ is clearly negative for incidences greater than the stall.

Substituting in equation (1) and integrating for the whole wing we obtain

$$L = -\tfrac{1}{2}\,\rho\, c\, V^2 \int_0^s y\,\Delta\,.\,dy$$

which may be re-written as

$$L = -\frac{\rho\, c\, V^4}{2\, p^2} \int_0^{sp/V} \left(\frac{yp}{V}\,\Delta\right) d\left(\frac{yp}{V}\right) \qquad \ldots\ldots(3)$$

Now yp/V is the increment of incidence at any point and Δ the differential lift increment between the element at that point and the corresponding element on the other side of the wing. Let

$$yp/V = \phi \text{ and } sp/V = \phi_s;$$

then

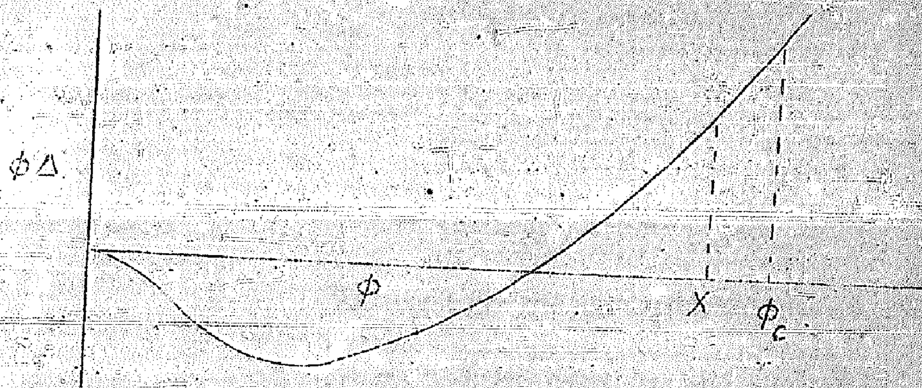
$$L = -\frac{\rho\, c\, V^4}{2\, p^2} \int_0^{\phi_s} (\phi\Delta)\, d\phi \qquad \ldots\ldots(4)$$

Plotting $\phi\Delta$ against ϕ the area under the curve as far as ϕ_s is proportional to the rolling moment at constant p and V, although a negative area corresponds to a positive, or destabilising moment.

Now consider the nature of the curve of $\phi\Delta$ against ϕ. When ϕ is zero there is no difference in incidence between the pair of elements, hence Δ is zero and the curve therefore passes through the origin. For a small ϕ, since we are assuming the initial incidence α to be above the stall, the pair of elements correspond to points P and R of Figure (2) and Δ is therefore negative; hence the curve of $\phi\Delta$ against ϕ starts out negatively from the origin for positive ϕ. As ϕ is increased, eventually the elements correspond to P_1 and R_1 for which Δ is again zero; the $\phi\Delta$ curve therefore also reaches zero. For still greater incidences (P_2 and R_2), Δ becomes positive, hence so also does $\phi\Delta$. The form of the curve of $\phi\Delta$ against ϕ is therefore as shown in Figure 3.

/Figure 3

FIG. 3



There is a certain incidence ϕ_c at which the total area under the curve is zero. Suppose the extreme differences in incidence $\pm\phi_s$ $(= \pm\frac{sp}{V})$ at the wing tips are $\pm\phi_c$ different from the initial incidence α. Since the area under the curve of Figure (3) is zero, the rolling moment is zero and the wing is in a stable state. That is to say, for a given aerofoil and given conditions above the stall, there is a value of p given by

$$p = \frac{V\phi_c}{s} \qquad \text{.........(5)}$$

at which the couple is zero. This is therefore a steady state of rotation, and is known as "auto-rotation" in the case of aeroplanes, or "whirling" in the case of bombs.

Suppose, now, the rate of rotation had been less than the steady value; ϕ_s would have been less than ϕ_c, corresponding to point X in Figure (3). The net area under the curve up to X is now negative, hence the total couple is positive; the rate of rotation is therefore increased until the couple becomes zero. Similarly it can be shown that if the rate of rotation had initially been greater than the steady value corresponding to ϕ_c, it will be reduced until the steady value is reached. Whirling is therefore a completely stable state, and for a given bomb, above the stall there is one steady rate of rotation corresponding to each pair of values of velocity and initial incidence (one p to each pair of V and α).

As we saw earlier in this section, whirling appears as a flat spin associated with rapid rotation of the bomb about the relative wind. If it occurs very early after release, in oscillation experiments, it can be confused with ordinary spins, but the following points help to distinguish it.

3.1 The time period of rotation in a whirl is different from the time period of oscillation in ordinary spins.

3.2 In an ordinary spin the amplitude tends steadily to decrease or increase - stability or instability - but in a whirl the amplitude (i.e. the semi-angle of the cone) changes very slowly and may increase or decrease slightly and irregularly.

3.3 Since whirling occurs if the initial incidence exceeds the stall, it should probably be found associated with large initial incidences;

it rarely occurs at angles of less than 40° with ordinary bombs.

Whirling is clearly an undesirable feature in a bomb since it will make accurate aiming impossible and may result in flat strikes with failure to detonate. It can only be eliminated by improving the stability of the bomb. This may mean increasing the slope of the $C_M - \alpha$ curve (increasing $\dot{M}_w$ negatively and decreasing $\frac{UT}{l}$) or simply by a modification which increases the stalling incidence. Little is known about the pitching moments of bombs at large angles of incidence, hence elimination of whirling cannot be achieved by aiming for increase of the stalling incidence, although this may be achieved accidentally. For example, in experiments with the 100 lb. M.C. bomb there were two variants identical except that one had an ogival nose and the other a bluff and rounded nose; their weathercock stabilities were almost identical yet the type with bluff and rounded nose had less tendency to whirl than that with the more streamlined nose. Other experiments also tend to confirm this fact - that bluff and rounded noses are less liable to whirl than more streamlined ones, even though the weathercock stabilities at moderate angles of incidence are not greatly different.

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